Omega meson as a chronometer and thermometer in hot-dense hadronic matter.

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Changes in the properties of the vector mesons in hot and dense hadronic matter, as produced in heavy ion collisions, lead to the intriguing possibility of the opening of the decay channel $\omega \rightarrow \rho\pi$, for the omega meson, which is impossible in free space. This along with the channel $\omega\pi \rightarrow \pi\pi$ would result in a decrease in its effective life-time enabling it to decay within the hot zone and act as a chronometer in contradiction to the commonly held opinion and would have implications vis a vis determination of the size of the region through pion interferometry. A new peak and a radically altered shape of the low invariant mass dilepton spectra appears due to different shift in the masses of ρ and ω mesons. The Walecka model is used for the underlying calculation for the sake of illustration.

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It is well established by now that the essential properties of the hadrons, once immersed in hot dense hadronic matter do change perceptibly. The spectral analysis of particles ejected from relativistic heavy ion collisions can give some insight into the physical properties of the system; any change in the spectrum offers an exciting possibility to study the structure of hadrons and the QCD ground state at finite temperature and density. The light vector mesons (ρ and ω) can act as indicators for the partial restoration of chiral symmetry, a symmetry which is broken in the hadronic ground state. Reliable informations on the evolving state of this hot and dense strongly interacting matter would hardly be possible from hadronic signals as these would be masked behind layers of complex dynamics. On the other hand, such inferences could perhaps be drawn from the dilepton (l^+l^-) spectrum which does not suffer from such strong distortions and carries information about the environment of the hadrons from which the pairs originate. These electromagnetic probes couple to hadrons through spin one ($J^P = 1^-$) mesons. Final spectra exhibit a resonant structure which, in the low mass regime includes the rho (ρ) and the omega (ω). The isovector rho meson of mass (m_ρ) 770 MeV has a full width (Γ_ρ) of 151 MeV which is mainly accounted for through the two pion decay channel. The isoscalar ω of mass (m_ω) 782 MeV has a far narrower width (Γ_ω) of 8.4 MeV since the two pion mode is forbidden by G-parity conservation and is allowed to decay into three pions with a consequent substantial reduction in phase space. It is generally believed that because of the narrow width of omega, which dictates a long lifetime ($\tau_\omega \sim 23$ fm/c) as compared to that of the ρ ($\tau_\rho \sim 1.3$ fm/c), the former (in contrast to the ρ) decays outside the hot and dense region, and thus while $\rho \rightarrow l^+l^-$ does provide information on the fireball, $\omega \rightarrow l^+l^-$ does not.

However, it is the contention of this letter, that this is not necessarily so.

Changes in the masses and decay widths in nuclear matter at finite temperature and density may indeed radically alter the scenario as would be argued below. Thus, both ρ and ω may serve as sensitive chronometers and thermometers of the evolving hadronic gas. We wish to draw attention to the fact that qualitatively interesting and amusing phenomena can occur in any scenario where the masses of different hadrons behave differently as a function of temperature and density. Thus under suitable conditions of temperature and density of its environment, the mass of the omega can exceed the sum of the masses of the ρ and the π and thereby the two particle $\rho\pi$ channel can open up. In a hadronic medium the channel $\omega\pi \rightarrow \pi\pi$ is also very important for the depletion of ω. Due to these two processes along with $\omega \rightarrow 3\pi$ the narrow ω can become dramatically broad in the medium.

Many authors [1–3] have investigated the issue of temperature dependence of hadronic masses within different models over the past several years. We employ one of the most extensively used and well tested models as far as nuclear matter calculations are concerned, namely the Walecka model [4]. The Walecka model comprises of the scalar σ, the ρ, ω and nucleon fields interacting through the Lagrangian

$$\mathcal{L} = g_\sigma \bar{N}\phi_\sigma N - g_{VNN}\Big[\bar{N}\gamma_\mu \tau^\alpha N - i\frac{\kappa_V}{2M}\bar{N}\sigma_{\mu\nu}\tau^\alpha N\partial^\nu\Big]V^\mu_\alpha \tag{1}$$

where, ϕ_σ and N are the sigma and nucleon fields and the generic vector field is denoted by V^μ_α, α running from 0 to 3, indexes quantities relevant for ω (when $\alpha = 0$) and for ρ ($\alpha = 1$ to 3); also $\tau_0 = 1$ and τ_i are the isospin Pauli matrices. The value of the σ mass has been taken to be $m_\sigma = 450$ MeV and the coupling constants $g_{\omega NN} \sim 10$, $g_{\rho NN} \sim 2.6$, $\kappa_\rho \sim 6.1$, $\kappa_\omega = 0$ and $g_\sigma \sim 7.4$, chosen so as to reproduce the saturation density and the binding energy per nucleon in nuclear matter.

The effective nucleon mass (which appears in the nucleon loop contribution to self energies of the rho and omega mesons) has been calculated, within the framework of the model defined above, in the Relativistic Hartree Approximation. The major contribution to the medium effects on the rho and omega mesons, in this approach, arises from the nucleon-loop diagram. For the

dressing of internal lines in matter we restrict ourselves to Mean Field Theory (MFT) to avoid a plethora of diagrams and to maintain internal consistency. It has been shown earlier [5] that the change in rho mass due to $\pi - \pi$ loop is negligibly small at nonzero temperature and zero density. It is found that the in-medium mass of ω (m_ω^*) decreases less rapidly than that of ρ (m_ρ^*) with temperature (T) and density (n_B) such that in a region of n_B and T (to be delimited later) the $\omega \to \rho\pi$ channel which in free space is kinematically forbidden because $m_\omega < m_\rho + m_\pi$ becomes possible in matter when $m_\omega^* > m_\rho^* + m_\pi$. Within the framework of the model adopted here, the mass of the rho meson decreases more rapidly than the mass of the omega because they couple to nucleons with different coupling strength, as is evident from the values of the coupling constant quoted in the previous paragraph. We do not observe any universal scaling law [6] in our calculation. Different rate of variation for rho and omega masses with temperature has been reported in Ref. [7] also. Since the Walecka model does not have chiral symmetry, it is rather difficult to predict something reliable on the pion mass in this model, especially in the MFT approximation [4,8]. On the other hand, in the models with chiral symmetry e.g. the Nambu-Jona-Lasinio model, and the linear sigma model with nucleon, it is well-known that the pion mass is almost unchanged in so far as one is in the Nambu-Goldstone phase. This is simply a consequence of the Nambu-Goldstone theorem in medium [9]; we thus adopt this approach of keeping the pion mass constant.

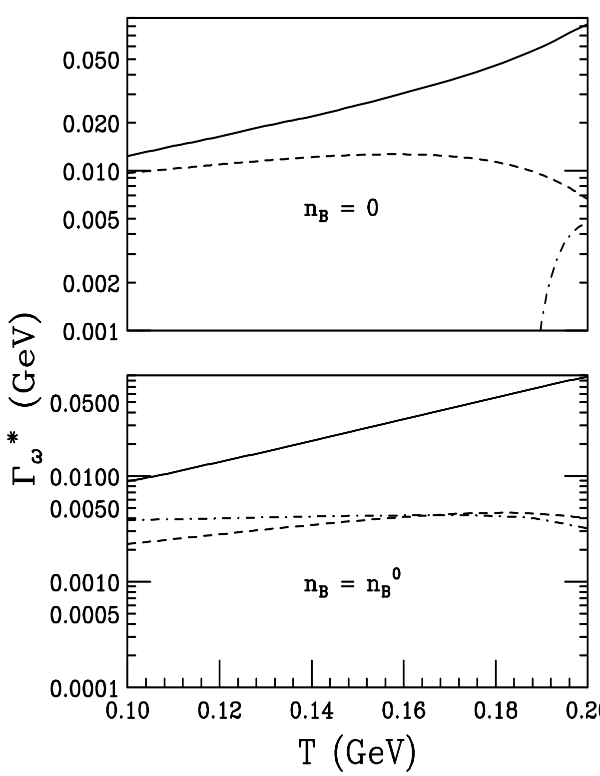

FIG. 1. In-medium decay widths of omega meson for $\omega \to \rho\pi$ (dot-dashed line) and $\omega \to 3\pi$ (dashed line) as a function of temperature at zero and normal nuclear density. The solid line indicates the total in-medium depletion rate of ω due to the above two processes along with the contribution from $\omega\pi \to \pi\pi$.

In order to delimit the extremities, it may be appropriate to remark that the decay $\omega \to \rho\pi$ is possible for a baryon density $n_B/n_B^0 \geq 0.3$ (n_B^0 being the normal nuclear matter density) at zero temperature, whereas at zero baryon density this is allowed for $T \geq 185$ MeV. The width for the decay $\omega \to \rho\pi$ when allowed is calculated by using the Lagrangian proposed by Gell-Mann, Sharp and Wagner (GSW) [10]

$$\mathcal{L} = \frac{\}_{\omega\pi\rho}}{\Updownarrow_\pi}\epsilon_{\mu\nu\alpha\beta}\partial^\mu\omega^\nu\partial^\alpha\vec{\rho}^\beta\cdot\vec{\pi} \tag{2}$$

and employing for the in-medium decay width the finite temperature cutting rules, one has

$$\Gamma^*_{\omega\to\rho\pi} = \frac{g^2_{\omega\pi\rho}}{32\pi m_\omega^{*3}m_\pi^2}\lambda^{3/2}(m_\omega^{*2}, m_\rho^{*2}, m_\pi^2) \times \Big[1 + f_{BE}(E_\pi) + f_{BE}(E_\rho)\Big] \tag{3}$$

where λ is the appropriate phase space factor (triangular function), while f_{BE} is the Bose-Einstein distribution for the pions and the rho mesons in equilibrium. The coupling constant $g_{\omega\rho\pi} \sim 2$ can be deduced from the observed decay $\omega \to \pi^0\gamma$ using the vector dominance model of Sakurai [11] for the $\rho\gamma$ vertex taking the process to occur through a virtual rho which converts to a photon. The three body decay width for $\omega \to 3\pi$ is estimated from the phenomenological effective Lagrangian [12]

$$\mathcal{L}_{\omega\ni\pi} = \{_{\omega\ni\pi}\epsilon_{\mu\nu\alpha\beta}\omega^\mu\epsilon^{\rangle|||}\partial^\nu\pi_\rangle\partial^\alpha\pi_|\partial^\beta\pi_{||} \tag{4}$$

the latin indices referring to isospin, avoiding for the present purpose the GSW model where this decay proceeds via a virtual rho ($\omega \to \rho\pi \to \pi\pi\pi$) in order to avoid the possibility of double counting when the threshold for the two body decay is crossed.

The resulting depletion rate of omega as a function of temperature at zero baryon density ($n_B = 0$) and at normal nuclear densities ($n_B = n_B^0$) is depicted in Fig. 1; and it may be noted that the two body channel opens up in the former case at a temperature ~ 185 MeV, while in the latter situation (normal nuclear density) this channel remains open even at zero temperature. The opening of the channel $\omega \to \rho\pi$ and the process $\omega\pi \to \pi\pi$ endows the omega-meson with a width comparable to that of the ρ meson as a result of which the lifetime of the omega meson reduces to ~ 2.3 fm/c which is comparable to the rho meson lifetime (~ 2.1 fm/c) under the same condition. Thus the omega meson gets promoted to be an effective probe for the early stages of hadronic matter formed in relativistic heavy ion collisions. This is in sharp

contradiction to the commonly held notion according to which the omega is too long-lived [13,14] to serve this purpose. However, as mentioned earlier the hadronic decay modes of rho and omega in the fire-ball are not very informative and that they are experimentally 'visible', so to say, through their dileptonic decay modes. Therefore, it is more relevant to evaluate the dilepton emission rate from the decay of unstable vector particles (ρ and ω) by using the generalized Breit-Wigner formula at a non-zero temperature and density [15]

$$\frac{dR}{dM} = \frac{2J+1}{\pi^2} M^2 T \sum_n \frac{K_1(nM/T)}{n} \times \frac{m_V^* \Gamma_{\rm tot}^*/\pi}{(M^2 - m_V^{*2})^2 + m_V^{*2}\Gamma_{\rm tot}^{*2}} m_V^* \Gamma_{V\to e^+e^-}^{\rm vac} \tag{5}$$

where $\Gamma_{\rm tot}^* = \Gamma_{V\to {\rm all}} - \Gamma_{{\rm all}\to V}$, K_1 is the modified Bessel function and $\Gamma_{V\to e^+e^-}^{\rm vac}(M)$ is the partial width for the leptonic decay mode for off-shell vector particles. We use the above equation to evaluate the invariant mass spectra of lepton pair originating from vector meson decays ($\rho \to e^+e^-$ and $\omega \to e^+e^-$). The emission of dileptons from rho and omega decay is affected due to changes in its mass and width (including collisional broadening due to $\omega\pi \to \pi\pi$, $\rho\pi \to \omega$ etc.) at non-zero temperature and density.

Putting the different processes together it can be seen from the solid line in Fig. 2 that the reduction in rho mass as compared to that of the omega is well reflected in the dilepton spectrum even if one includes the contribution from the pion annihilation channel $\pi\pi \to e^+e^-$. For comparison, the dashed line shows the sharp omega peak with $\omega \to \rho\pi$ and $\omega\pi \to \pi\pi$ closed. Also if one were to use unmodified free meson properties it would be impossible to resolve the rho and omega peaks in the dilepton spectrum (dot-dashed curve).

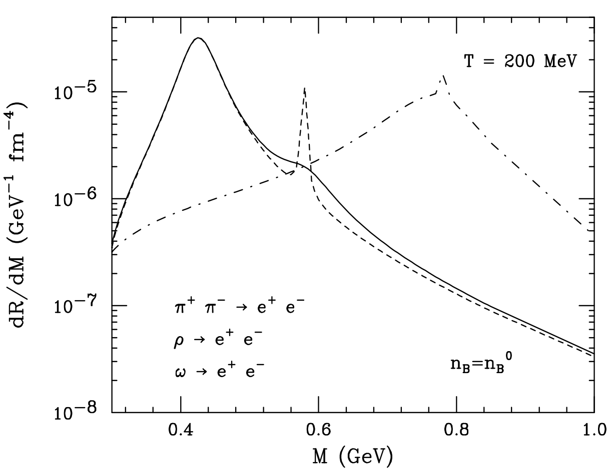

FIG. 2. Invariant mass distribution of lepton pairs from the decays $\omega \to e^+e^-$, $\rho \to e^+e^-$ and the reaction $\pi\pi \to e^+e^-$ at $n_B = n_B^0$. The solid line corresponds to the case when Γ_{tot}^* includes $\omega \to 3\pi$, $\omega \to \rho\pi$ and $\omega\pi \to \pi\pi$ for the omega meson; $\rho \to \pi\pi$ and $\rho\pi \to \omega$ for the rho meson. The dashed line shows the result with $\omega \to 3\pi$ only where the other two channels, as is often done, are ignored. Dot-dashed line indicates the yield without any medium effect whatsoever.

The observed dilepton spectra originating from an expanding hadronic system is obtained by convoluting the static (fixed temperature) emission rate with the expansion dynamics. In this work we use the simple Bjorken-like model [16] of boost invariant longitudinal expansion to estimate the dilepton yield from an expanding hadronic system. In Fig. 3 we present the dilepton yield for initial baryon density $n_B = 2n_B^0$ (solid line) and $n_B = n_B^0$ (dashed line) for $T_i = 200$ MeV and $T_F = 130$ MeV. The dot-dashed line indicates the dilepton spectrum when medium effects on hadronic masses and decay widths are not considered. The kink in the invariant mass plot of the dilepton yield at $M = 680$ MeV (dashed curve), due to omega decay survives even after the space time evolution of the system is taken into account. Dramatic effects on the dilepton spectra due to the broadening of omega should be discernible in experiments not involving expansion scenario such as investigations with the upcoming HADES lepton pair spectrometer at GSI.

The broadening of the ω meson due to different mechanisms have been reported recently in the literature (see e.g. [3,7,17]). Pisarski [3] has argued that the ω-width could increase by an order of magnitude due to the reduction in pion decay constant connected with chiral symmetry restoration, which in turn increases the coupling $g_{\omega\pi\rho}$. In another approach [17] ω in motion with respect to the medium could couple through $N\bar{N}$ excitation with σ, which subsequently decays to two pion state, resulting a large broadening of ω. However, if the ω is at rest such broadening of ω is absent, whereas the broadening mechanism proposed in the present work is possible even if the ω is at rest. In the spectral function approach proposed by Klingl et al [7] ω becomes broad but still can be treated as a quasi particle, supporting the basis of the present paper. The opening of the new channel in a thermal bath has a contribution similar to the channel $\omega \to 3\pi$, which is the most dominant channel in vacuum, however, in a thermal bath the most dominant process for the depletion of omega is $\omega\pi \leftrightarrow \pi\pi$. We emphasize at this point that for a short lived resonance (R) which decays within the medium, the width of the dilepton spectra is actually the rate at which it equilibrates ($\Gamma_{\rm tot} = \Gamma_{R\to{\rm all}} - \Gamma_{{\rm all}\to{\rm R}}$), involving in principle various processes in which R participates. It may be borne in mind that although elastic scattering contributes to kinetic equilibrium it has as such no direct effect on chemical equilibration of the system while of course such elastic processes are of importance in phe-

nomena such as viscosity etc. Indeed elastic scattering changes the momentum of the colliding particles but the nature of the particles remains unaltered and hence this process does not contribute directly to the decay life time in the bath. However, effects of elastic scattering on the broadening of vector meson width has been considered in the literature [18].

Furthermore, the ratio of the number of vector mesons decaying to lepton pairs inside ($N_{\rm in}$) to those decaying outside ($N_{\rm out}$) the hot zone may be estimated to be (see e.g. [19]) $N_{\rm in}/N_{\rm out} = (1-\exp(-\Gamma_{\rm tot}R_T))/\exp(-\Gamma_{\rm tot}R_T)$ where R_T is the size of the system. For both ρ and ω (now with a considerably broadened omega) the above ratio turns out to be much greater than unity. This indicates that in the presence of nuclear matter at finite temperature a substantial number of omega mesons decay inside the reaction volume and thus can act both as a chronometer and a thermometer for hot hadronic matter formed in relativistic heavy ion collisions.

Detailed measurement of the photoproduction of lepton pairs should provide invaluable insights into the creation, propagation and decay of vector mesons inside the nuclear medium. Changes in the rho and omega masses would reflect directly in the dilepton invariant mass spectrum due to the quantum interference between rho and omega mediated processes in the photoproduction of lepton pairs (CEBAF). CERES collaboration [20] has also planned to upgrade their experiment to improve the mass resolution so that the rho and omega may be disentangled under the condition mentioned above. It is argued [21] that the omega meson, due to its long life time (23 fm/c), complicates the extraction of Hanbury-Brown Twiss (HBT) radii from the correlation function, because the ω can distort the correlator to a highly non-Gaussian shape. An order of magnitude reduction in the life time of the omega due to the $\rho\pi$ decay and $\omega\pi \to \pi\pi$ reaction in the medium should, however, remove such complications.

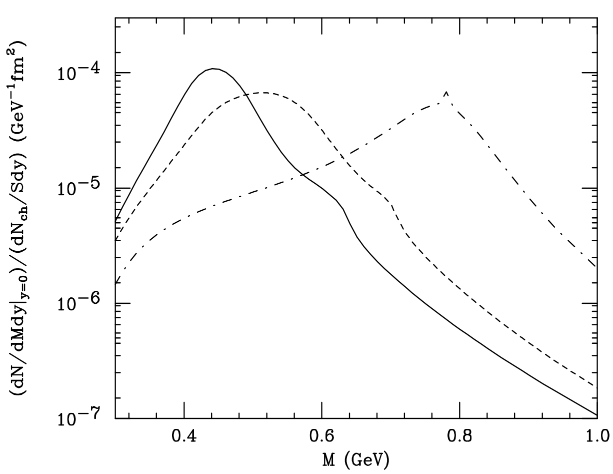

FIG. 3. Invariant mass distribution for dilepton yield from an expanding system for the decays $\omega \to e^+e^-$, $\rho \to e^+e^-$ and the reaction $\pi\pi \to e^+e^-$ (see text). S and dN_{ch}/dy denote the transverse area of the overlapped region and charge multiplicity respectively.

Therefore, our present observation has direct relevance to all those experiments measuring dilepton emission from hot and dense matter in the low invariant mass region and HBT interferometry. A small mass difference between ρ and ω mesons in vacuum makes it very difficult to disentangle the two peaks in the invariant mass spectra for dileptons. However, according to the present calculation, since the two peaks are widely separated, it should be possible to observe them through the radically altered shape of the dilepton spectra. Various aspects of this novel phenomena and its consequences on experimental observables are being pursued vigorously.

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